High pulse energy Yb:YAG MOPA and non-linear frequency conversion module for remote sensing applications

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Abstract— **Efficient energy storage and extraction from a solid state laser is important for pulsed laser applications such as laser remote sensing of stratospheric ozone or tropospheric wind velocities. Our approach to meeting the remote sensing wavelength requirements involves developing a high pulse energy 1.03 μm Yb:YAG MOPA system followed by non-linear frequency conversion to 1.5 μm for global wind sensing or to the 305 nm and 320 nm UV wavelengths for DIAL based detection of stratospheric ozone concentration. In this paper, we present designs for such a system, and preliminary results on parts of the overall system.**

I. Introduction

Efficient energy storage and pulsed extraction from a solid state laser is important for applications such as remote sensing of stratospheric ozone concentration or tropospheric wind velocities. Our approach to meeting the remote sensing wavelength requirements involves developing a high pulse energy Yb:YAG MOPA system followed by non-linear frequency conversion to 1.5 μm for global wind sensing[1] or to the 305 nm and 320 nm UV wavelengths for DIAL based detection of stratospheric ozone concentration.

Our laser system design is based on the master oscillator, power amplifier (MOPA) configuration. The MOPA configuration provides the ability to tailor the pulse width, beam divergence, and spectral width of the output pulses with low power components prior to the power amplifier. The scaling to high output pulse energy is determined by the power amplifier design. Further, the advantage of the MOPA architecture as opposed to an oscillator is that it offers a soft failure mode and allows scaling by implementing power-amplifiers in the chain.

However, for efficient pulsed energy extraction in each power amplifier, the fluence at the input must be at least equal to the Yb:YAG saturation fluence (J_{sat} = 9.6 J/cm^2). Because the optical damage fluence for 10 ns Q-switched pulses is approximately 10 J/cm^2, it is not possible to extract the stored energy from Yb:YAG amplifiers efficiently without causing optical damage. However, since the optical damage fluence for a 1 micro-second pulse is 100 J/cm^2, it is possible to saturate and extract the stored energy without optical damage using micro-second signal pulses.

In this μs pulse MOPA system, our choice of Yb:YAG as the gain material as opposed to a more established material like Nd:YAG was partially motivated by the smaller emission cross-section of Yb:YAG. The smaller emission cross-section of Yb:YAG compared to Nd:YAG allows storage of more energy for a given small signal gain coefficient($g_0 l$). Depending on the specifics of the amplifier design, the smaller gain cross-section of Yb:YAG allows us to store ~ 10 times more energy per unit volume then Nd:YAG. Thus, by careful choice of gain material and signal pulse width, it is possible to saturate and extract efficiently a significant fraction of the stored energy without optical damage to the crystal.

The present all solid-state, laser-diode pumped, μs pulse Yb:YAG MOPA system is designed to generate a one micro-second ($\Delta\tau$ = 1 μs) 100 mJ pulse at a 10 Hz repetition rate. High brightness laser-diodes are used to pump the Yb:YAG MOPA system which consists of a master-oscillator, pre-amplifier, and a 100 mJ power amplifier. The Yb:YAG amplifiers are designed with the end-pumped zig-zag slab geometry. The Yb:YAG MOPA can be made to operate with 1 MHz transform limited linewidth with the use of etalons in the master-oscillator to make it operate in a single longitudinal mode. Demonstration of 100 mJ pulse output is a critical first step toward the demonstration of a 10 J/pulse Yb:YAG MOPA. In addition to meeting the long term laser transmitter goals for remote wind sensing, we have shown that a 10 J/pulse MOPA meets the demands of an all solid state laser illuminator that achieves S/N = 10, with a target resolution of 20 cm at distances up to 4000 km [2].

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II. High Pulse Energy Yb:YAG Laser Design Specifications

A. Yb:YAG micro-chip Master Oscillator Module

At the heart of a coherent MOPA system is a highly coherent continuous-wave (cw) master oscillator (MO). Based on the work of Taira, we have built a 0.5 W cw master-oscillator that is shaped into 1 µs pulses at a 10 Hz repetition rate with the aid of an acousto-optic modulator. These pulses are then amplified in a pre-amplifier and a 100 mJ slab amplifier.

B. Pre-Amplifier Module and 100 mJ slab amplifier module

Pre-amplifier slabs 1 and 2 are designed to be double-passed as shown in Figure 1, where the 1 micro-Joule pulses shaped by the acousto-modulator are amplified to the 7 mJ level. The end-pumped [6] slab dimensions are 0.4 mm x 0.4 mm x 11 mm. Each slab is pumped with 120 W of cw power with cw fiber-coupled LDs, modulated at 10 Hz with a 1 % duty cycle (i.e. 0.120 J per pulse, pump energy).

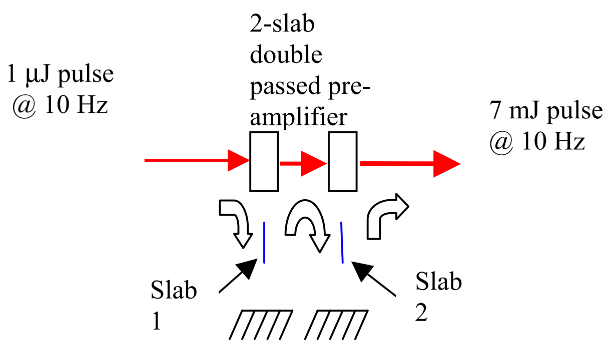

Fig. 1 Schematic of pre-amplifier stage of MOPA system

The average pump power is thus 1.2 W. The small signal gain, g_0l, in each slab is conservatively set at 2.25 to prevent the onset of parasitic oscillations. As a consequence, the pulse output of the first slab is 87 uJ pulse, and the pulse output of the second slab is 7 mJ.

In the next stage of amplification, we expect the 7 mJ pulses to be amplified to the 100 mJ level in an end pumped double-pass, slab amplifier of dimensions width = 1.05 mm, length = 11 mm and thickness = 1.05 µm. The pump power required is approximately 750 W cw, or about 7.5 W of average power when operated at the 1 % duty cycle.

On a practical note, parasitic oscillations can limit the gain achievable in a slab lasers and amplifiers and therefore limit the stored energy. We propose to suppress parasitic oscillations in each amplification stage of the MOPA system by choosing the aspect ratio (i.e. width to thickness ratio) of the slab carefully and polishing the edge faces with a wedge angle. This approach has been demonstrated to be effective in the first edge-pumped Yb:YAG zig-zag slab laser oscillator assembled by Rutherford [3].

Another key to improved energy extraction with reduced thermal distortion in MOPA laser systems is the use of super-gaussian spatial profile pulses. Propagation of super-gaussian pulses through saturated amplifiers results in better extraction of the stored energy because the incoming beam more uniformly fills the slab and utilizes a greater fraction of the inverted population. Mansell has developed micro-miniature optical device that converts a gaussian intensity profile beam into a super-gaussian profile beam and we propose to use these devices in the Yb:YAG power amplifiers[4].

Further average power scaling of this MOPA system to higher pulse energy levels and higher repetition rates will likely involve multi-passed edge-pumped Yb:YAG slabs[3]. The edge pumping innovation allows the realization of a compact, conduction cooled, reliable, laser engine that will permit operation at pulse energy levels that will meet the requirements for global remote wind sensing and stratospheric ozone concentration measurement applications. Edge-pumped slab amplifiers inherently allow energy to be stored and extracted in a variety of pulse formats depending on the application. By careful engineering it is possible to extract both high pulse energies and high average power from an edge-pumped slab amplifier system [5].

III. Non-Linear Frequency Conversion

The high pulse energy 1.03 µm Yb:YAG MOPA system under development has applications in remote wind sensing if the output can be converted to the longer infrared wavelengths. We are investigating frequency conversion using optical parametric amplifiers (OPAs) based on both waveguide and bulk periodically poled lithium niobate (PPLN). The goal is to down-convert to the telecommunications bands to take advantage of the tunable laser oscillators in the C and L band region. This band also allows the use of fiber pre-amplifiers, quantum noise limited detectors, and fiber based components for coherent detection of signals. To meet the source requirements for ozone detection, frequency conversion to the ultraviolet is possible by harmonic and sum generation steps. As illustrated in Figure 2, the key is to utilize the advantages of the Yb:YAG system for energy storage and extraction followed by efficient frequency conversion to meet the various remote sensing application needs.

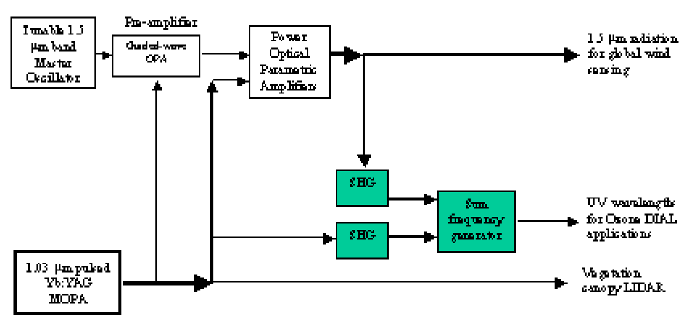

Fig. 2 *Schematic of non-linear optics approaches for various applications*

However, since the Yb:YAG MOPA is still under development, we have chosen to pursue demonstration of some of the non-linear optics modules in parallel, using existing Nd:YAG laser sources. Since the output radiation of a Nd:YAG MOPA system at 1.064 um is close to the expected 1.03 um output of the Yb:YAG MOPA system, the non-linear optics module will need to be only slightly modified to meet the final energy and wavelength requirements of the various remote sensing applications. Using flash-lamp pumped Nd:YAG rods as amplifiers, we have amplified a modulated non planar ring oscillator (NPRO) to the 100 mJ/µs level. Figure 3 shows a schematic of a 1.064 um MOPA that we have built in the laboratory.

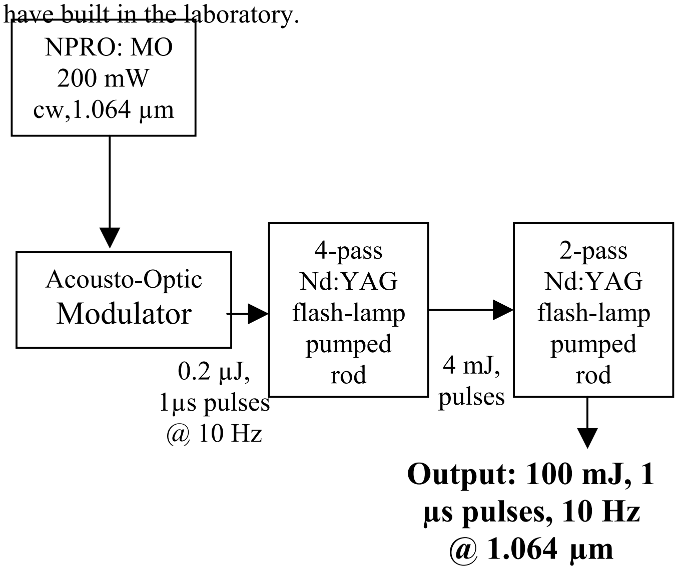

Fig. 3 Schematic of Nd:YAG MOPA test-bed

Using a small fraction of this 100 mJ/µs MOPA energy, we are at present working on a 1.5 um band wave-guide based periodically poled lithium niobate (PPLN) optical parametric amplifier (OPA). This system schematic is shown in Figure 4.

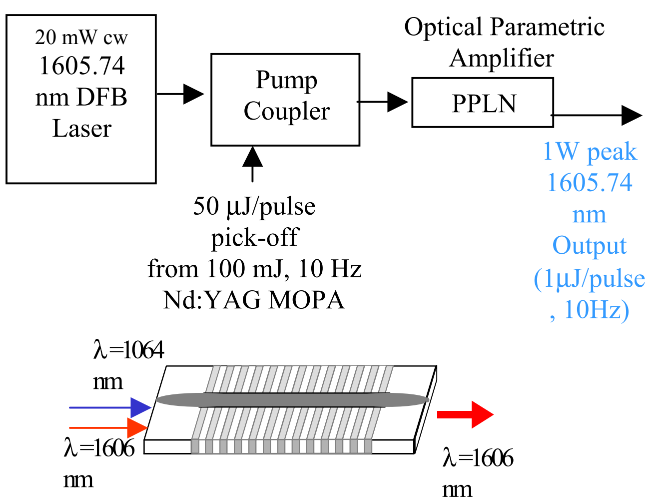

Fig. 4 Schematic of waveguide based PPLN OPA

In the first test versions of the PPLN waveguide devices, gains of ~4-5 dB at the signal wavelength have been measured. By fabricating devices with longer interaction lengths and consequently higher conversion efficiency, we expect to measure > 20 dB signal gain in this OPA.

This waveguide-based PPLN OPA will be followed by bulk PPLN OPA's to scale the pulse energy to the 20-30 mJ level. Depending on the availability of pump pulse energy, the system under construction can be scaled up to higher pulse energies in the 1.5 um band to meet the global wind sensing application requirements.

To meet the laser source requirements for Ozone DIAL (Fig.2), the amplified 1.5 µm band pulse energy will need to be frequency doubled to the appropriate red wavelengths and mixed with the green wavelength pulse to generate the required UV wavelengths.

At present, we have completed a design of such a system and are in the process of demonstrating adequate gains in the 1.5 µm band in PPLN based optical parametric amplifiers.

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